

Research Note

Effect of a Reactive Oxygen Species–Generating System for Control of Airborne Microorganisms in a Meat-Processing Environment[†]

J. R. PATEL* AND X. NOU

U.S. Department of Agriculture, Agricultural Research Service, Food Safety Laboratory, 10300 Baltimore Avenue, BARC-East, Beltsville, Maryland 20705-2350, USA

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ABSTRACT

The effectiveness of reactive oxygen species (ROS)–generating AirOcare equipment on the reduction of airborne bacteria in a meat-processing environment was determined. *Serratia marcescens* and lactic acid bacteria (*Lactococcus lactis* subsp. *lactis* and *Lactobacillus plantarum*) were used to artificially contaminate the air via a six-jet Collison nebulizer. Air in the meat-processing room was sampled immediately after aerosol generation and at various predetermined times at multiple locations by using a Staplex 6 stage air sampler. Approximately a 4-log reduction of the aerial *S. marcescens* population was observed within 2 h of treatment ($P < 0.05$) compared to a 1-log reduction in control samples. The *S. marcescens* populations reduced further by ~ 4.5 log after 24 h of exposure to ROS treatment. Approximately 3-log CFU/m³ reductions in lactic acid bacteria were observed following 2-h ROS exposure. Further ROS exposure reduced lactic acid bacteria in the air; however, the difference in their survival after 24 h of exposure was not significantly different from that observed with the control treatment. *S. marcescens* bacteria were more sensitive to ROS treatment than the lactic acid bacteria. These findings reveal that ROS treatment using the AirOcare unit significantly reduces airborne *S. marcescens* and lactic acid bacteria in meat-processing environments within 2 h.

Contamination of meat products by microorganisms is a major economic problem in the meat industry. Contamination can occur at various stages of animal processing and meat fabrication (22). Prevention and/or reduction of such contamination is a major objective of hazard analysis critical control point systems and related in-house food safety programs such as good manufacturing practices. There are several strategies available to reduce the populations of microorganisms on carcasses. These include carcass trimming, carcass washing, organic acid treatments, and combinations of the above (4). In addition, programs such as cleaning and maintenance of plant and equipment and plant sanitation are included but may not involve steps to prevent air as a source of contamination of food and equipment.

Air has long been recognized as a source of microbial contamination in a range of food processing plants including dairy (12, 20), beef (3, 9, 22), pork (13, 17), and poultry products (15, 25). Rahkio and Korkeala (19) reported a strong association between aerobic viable counts on beef carcasses and the levels of airborne microbial contamination in the processing environment. It is essential to monitor and reduce the airborne microbial levels in the meat-processing environment.

Various technologies have been developed for the reduction of airborne microorganisms in food processing environments. UV light is widely used to inactivate airborne bacteria and mold in food-processing areas (7). The use of filtration along with electrostatic precipitation is used to capture airborne particles (23) that harbor bacteria. The electrostatic space charge system has been shown to be highly effective in reducing dust and pathogens in the air and on surfaces (1). This system reduced airborne *Salmonella enterica* serovar Enteritidis contamination by 95% in caged layer rooms (10). The effect of electrostatic space charge on bacteria in biofilms was studied by Arnold and Mitchell (2). They found a 99.8% reduction of mixed populations of bacteria from stainless steel surfaces in a poultry plant. A patented air-cleaning system (AirOcare Inc.) utilizes a high-frequency controlled pulse of electric current in a series of reaction chambers inside the unit to convert part of the oxygen in the air into various reactive oxygen species (ROS). These ROS are believed to be capable of oxidizing molds, mildew, bacteria, and viruses. The objective of this study was to determine the efficacy of ROS-generating equipment in reducing airborne bacteria in a meat-processing environment.

* Author for correspondence. Tel: 301-504-7003; Fax: 301-504-8438; E-mail: jitu.patel@ars.usda.gov.

† Mention of trade names or commercial products does not imply recommendation or endorsement to the exclusion of other products by the U.S. Department of Agriculture.

MATERIALS AND METHODS

Bacterial cultures. *Lactococcus lactis* subsp. *lactis* ATCC 11454, *Lactobacillus plantarum* NCDO 955, and *Serratia marcescens* (USDA 2772) strains were from the Food Safety Labo-

ratory culture collection. Lactic acid bacteria were maintained individually in lactobacilli deMan Rogosa Sharpe broth (MRS; Acumedia, Lansing, Mich.) containing 10% glycerol and were stored at -80°C , whereas tryptic soy broth (TSB; Difco Laboratories, Detroit, Mich.) with 10% glycerol was used for the *S. marcescens* strain. Frozen cultures were partially thawed at room temperature (20°C) for 15 min; *S. marcescens* was streaked on tryptic soy agar slants (Difco), and lactic acid bacterial cultures were streaked on lactobacilli MRS agar slants (Acumedia) and incubated at 35°C for 24 h. Actively growing lactic acid bacterial strains were individually transferred to 100 ml of MRS broth, and the *S. marcescens* culture was transferred to 100 ml of TSB broth followed by 24-h incubation at 35°C . Cells were harvested by centrifugation at $5,000 \times g$ for 10 min and resuspended in phosphate-buffered saline (PBS; 50 mM). Each individual bacterial culture was enumerated by serially diluting the cultures in sterile 0.1% peptone water (Difco) and spiral plating (WASP; Microbiology International, Frederick, Md.) onto duplicate R₂A agar (Difco) and MRS agar plates. The average bacterial population of strains used in aerosol formation was ~ 9 log CFU/ml.

Experimental facility. The establishment was one of the oldest animal-slaughtering facilities (>80 years old) in the United States and, therefore, did not have the most modern air-handling system. Further, the establishment was not used regularly for animal slaughter. ROS-generating equipment (model MDS 202BS, AirOcare Inc., Rockville, Md.) was installed inside the meat-processing room. The room (30 ft long by 16 ft wide by 10 ft high) was primarily used for further processing of meats. It was equipped with further processing machinery such as a band saw, brine pump, vacuum tumbler, meat grinder, bowl chopper, mixer, and vacuum stuffer, which are used to divide meat carcasses into primal cuts, brine inject solid muscles, mince or grind meat for sausage formulation, and also emulsify meat batters for frankfurters.

ROS-generating console unit. The ROS-generating console unit (AirOcare Inc.) was installed on the wall with a discharge pipe in a room. The unit is based on a system of tubular arrays and a very specific electrical field configuration to generate steady-state cold plasma. As air circulates through the unit's reaction chambers, part of the oxygen is electrically excited and converted to various ROS on a temporary basis. Given the difference in electrical potential across the glass walls of the tubular arrays inside the reaction chambers, several reactions involving oxygen occur. ROS include low levels of ozone (O_3), vapor hydrogen peroxide, and other oxidative compounds. A monitoring device regulates low levels of O_3 as the marker to determine contamination and adjusts according to the requirement of the application. Since the room air is circulated through the AirOcare unit, the short-lived ROS are able to carry on their oxidizing benefits.

Aerosol generation and sampling. Natural microbial load in the meat-processing room was evaluated using a Staplex 6-stage air sampler (Staplex Inc., Brooklyn, N.Y.) and R₂A agar media, using the procedure described below. Low levels of natural contamination (<1.5 log CFU/m³) were reduced to nondetectable levels within 2 h of ROS exposure. Therefore, aerosols were generated to increase the microbial contamination in the meat-processing room.

Equal volumes (25 ml) of *S. marcescens*, *L. lactis*, and *L. plantarum* suspensions were mixed and transferred to a six-jet Collison nebulizer (model CN-25, BGI, Waltham, Mass.). The nebulizer was placed 12 in. above the predetermined sampling sites, and bacterial suspensions were aerosolized for 15 min at

each site, using 20-lb/ft² air pressure. The initial population of aerosolized bacteria (0 h) was determined at three locations by using a Staplex 6-stage air sampler prior to turning the ROS-generating unit on. Sampling locations 1, 2, and 3 were 4, 12, and 18 ft away from the ROS console, respectively. Air samples were taken at 2, 4, 8, and 24 h during the treatment. The air sampler was kept about 36 in. above the floor at each location. The sampler was calibrated with an RC-50 totometer (Staplex) to maintain a flow rate of 28.3 liters/min during the sampling period. MRS and R₂A agar plates were used in the Staplex sampler for detecting mixtures of lactic acid bacteria and *S. marcescens*, respectively, in the airborne environment. After pulling air samples for 15 min, the plates were incubated at 35°C for 48 h. The control experiment was carried out using the same procedure as the treatment exposure; however, under the control conditions the ROS-generating unit was turned off. Each experiment was started on Monday morning and completed within a 24-h period. The experiment was replicated three times.

Statistical analysis. The total colony counts of four plates obtained at each sampling period and each location were converted to log CFU per cubic meter. The data obtained from three replicates were analyzed by two-way analysis of variance using a "Proc Mixed" statement (SAS 8.2, Cary, N.C.) for effects of treatment, location, sampling time, and interaction. For each response, covariance analysis, which allows correlation among levels of location, time, or both, was utilized. In all cases, the level of statistical significance used was set at *P* values of <0.05 .

RESULTS

The effect of ROS generated by the AirOcare ROS system on airborne *S. marcescens* population is shown in Table 1. Airborne *S. marcescens* populations varied from 3.99 to 4.88 log CFU/m³ immediately following aerosolization at different sampling locations. Gradual reduction of *S. marcescens* populations was observed in the control samples. The reduction of airborne *S. marcescens* was from 0.08 log (site 3) to 0.81 log (site 1) 2 h following aerosolization in the control treatment. In contrast, a >4 -log reduction (*P* < 0.05) in the *S. marcescens* population was observed within 2 h of ROS treatment. Extended ROS exposure of up to 24 h resulted in nondetectable *S. marcescens* level at site 2. *S. marcescens* populations after ROS treatments were significantly lower than those of the corresponding control samples for 4, 8, and 24 h. While *S. marcescens* populations decreased with time in control samples, the reduction was ca. 2 log CFU/m³ after 24 h, compared with a ca. 5-log CFU/m³ reduction of this bacterium after 24 h of ROS treatment. Sampling sites did not have a significant effect on the recovery of airborne *S. marcescens* populations, as the populations detected at different sampling sites were similar (*P* > 0.05) at specific sampling times of ROS treatment.

Initial populations of aerosolized lactic acid bacteria varied from 4.23 log CFU/m³ at site 3 to 4.97 log CFU/m³ at site 1 (Table 2). Initial lactic acid bacterial populations following ROS exposure were higher than the initial lactic acid bacterial populations of control samples; however, the difference was not significant. Approximately 3-log CFU/m³ reductions (*P* < 0.05) in lactic acid bacteria were observed at each location following 2 h of ROS treatment.

TABLE 1. *Serratia marcescens* populations in meat-processing room following treatment with ROS-generating system

Sampling site ^a	Treatment	Bacterial populations (log CFU/m ³) at time point ^b :				
		0 h	2 h	4 h	8 h	24 h
1	Control	4.62 AX	3.81 AXY	2.90 AYZ	2.09 AZ	2.22 AZ
	ROS	4.88 AX	0.87 BY	0.28 BY	0.28 BY	0.38 BY
2	Control	4.13 AX	3.97 AX	2.82 AY	2.48 AY	2.22 AY
	ROS	4.77 AX	0.28 BY	0.57 BY	ND BY	ND BY
3	Control	3.99 AX	3.91 AX	2.71 AY	2.47 AY	2.19 AY
	ROS	4.69 BX	ND BY	ND BY	ND BY	0.28 BY

^a 1, mixer by the kill room entry door; 2, weighing scale; 3, cutting table.

^b For each site, means in the same column with different letters (A, B) are significantly different ($P < 0.05$); means in the same row with different letters (x, y, z) are significantly different ($P < 0.05$). ND, nondetectable.

While extended ROS exposure further reduced lactic acid bacteria at each location over 8- and 24-h treatments, the reduction during these periods was not significant. Lactic acid bacterial populations obtained from ROS-treated sites after 2 and 4 h were significantly lower than the lactic acid bacterial populations from corresponding control samples. As with *S. marcescens*, a gradual reduction of lactic acid bacteria was also found in untreated samples. At each sampling period of 8 or 24 h, airborne lactic acid bacterial populations obtained from control and ROS-treated samples were similar, except for sampling site 1, where lactic acid bacterial populations in ROS-treated samples were significantly lower than those populations obtained after 8 h of treatment.

DISCUSSION

Initial air sampling at three sites in the meat-processing room revealed very low levels of background airborne bacterial loads (<1.5 log CFU/m³). These results were comparable to ~ 1.5 log CFU/m³ airborne microbial counts in commercial food-processing facilities that were reported by Cundith et al. (4), but lower than other reported airborne bacterial loads, such as 2.0 to 2.3 log CFU/m³ (19) and 2.4 to 3.4 log CFU/m³ (18) in beef slaughterhouses, and 2.5 to 3.6 (14) and 2.3 to 3.1 log CFU/m³ (17) in pork processing plants. Since ROS treatment of low levels of airborne bacteria resulted in nondetectable levels at each sampling site within 2 h (data not shown), we increased airborne microbial load by using aerosolization. *S. marcescens* and lactic

acid bacteria were used in this study because these bacteria are known to occur in meat products (6, 11) and are also found in meat-processing environments (8). In the meat industry, large concentrations of *S. marcescens* cause spoilage of fresh and ready-to-eat meats, resulting in off-flavor, color changes, rancidity, and slime (5, 16, 24).

Air is an important vehicle for bacterial contamination in slaughterhouses and meat-processing facilities (17, 19, 25). Effective reduction of airborne pathogenic and spoilage bacteria should be an integral part of the concerted efforts to reduce or prevent potential cross-contamination in meat and meat products. Cundith et al. (4) used germicidal air-cleaning console units and found 1- to 1.5-log reductions in airborne bacteria and molds in different areas of a meat-processing facility. Similar results were reported by St. Georges and Feddes (23), who used air filtration and electrostatic precipitation. Electrostatic space charge systems reduced total aerobic bacteria in broiler breeder facility by 76%, resulting in fewer *Salmonella Enteritidis*-positive hens and chicks (21). Burfoot et al. (3) studied the effect of HEPA filter ultraclean air in a beef slaughterhouse. They observed reduced contamination on beef carcasses via airborne routes. This study showed the significant effect of ROS exposure in reducing airborne microorganisms in a meat-processing environment. ROS are moderate to strong oxidizing agents. They inactivate bacteria by rupturing the cell wall. The ROS level (monitored by an O₃ marker) of 0.0389 ppm used in this study is well below the permissible (0.1 ppm) 8-h exposure limit for a worker. Because of its

TABLE 2. Populations of lactic acid bacteria in meat-processing room following treatment with ROS-generating system

Sampling site ^a	Treatment	Bacterial populations (log CFU/m ³) at time point ^b :				
		0 h	2 h	4 h	8 h	24 h
1	Control	4.54 AW	3.76 AX	2.68 AY	2.08 AYZ	1.90 AZ
	AirOcare	4.97 AX	2.05 BY	1.94 BY	1.53 BY	1.80 AY
2	Control	4.41 AW	3.80 AX	2.64 AY	2.05 AYZ	1.74 AZ
	AirOcare	4.90 AX	2.04 BY	1.72 BY	1.68 AY	1.68 AY
3	Control	4.23 AX	3.65 AX	2.22 AY	2.22 AY	1.40 AY
	AirOcare	4.81 BX	1.92 BY	1.37 BY	1.70 AY	1.53 AY

^a 1, mixer by the kill room entry door; 2, weighing scale; 3, cutting table.

^b For each site, means in the same column with different letters (A, B) are significantly different ($P < 0.05$); means in the same row with different letters (w, x, y, z) are significantly different ($P < 0.05$).

short life, undesirable effects of ROS treatment are considered to be minimal, if not inconsequential. The reduction of airborne microorganisms using the ROS-generating system seemed to be more efficient than those reported with other approaches, such as electrostatic precipitation (23) and germicidal air purification console units (4).

Based on these findings, our study reveals that active oxygen treatment using the ROS-generating AirOcare unit significantly reduces airborne *S. marcescens* and lactic acid bacteria in a meat-processing environment within 2 h. The treatment is more inhibitory to *S. marcescens* than to lactic acid bacteria. The difference in sensitivity of these bacteria to ROS could be attributed to differences in cell wall structure. The unit has an application for controlling airborne contamination in meat-processing facilities. Air with fewer bacteria in meat-processing environments could help improve meat shelf life and reduce cross-contamination in meats.

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REFERENCES

- Arnold, J. W., D. H. Boothe, and B. W. Mitchell. 2004. Use of negative air ionization for reducing bacterial pathogens and spores on stainless-steel surfaces. *J. Appl. Poult. Res.* 13:200–206.
- Arnold, J. W., and B. W. Mitchell. 2002. Use of negative air ionization for reducing microbial contamination on stainless-steel surfaces. *J. Appl. Poult. Res.* 11:179–186.
- Burfoot, D., R. Whyte, D. Tinker, M. Howell, K. Hall, J. Holah, D. Smith, R. White, D. Baker, and J. McIntosh. 2006. Importance of airborne contamination during dressing of beef and lamb carcasses. *J. Food Prot.* 69:2828–2836.
- Cundith, C. J., C. R. Kerth, W. R. Jones, T. A. McCaskey, and D. L. Kuhlers. 2002. Air-cleaning system effectiveness for control of airborne microbes in a meat-processing plant. *J. Food Sci.* 67:1170–1174.
- Dykes, G. A., T. E. Cloete, and A. von Holy. 1994. Identification of *Leuconostoc* species associated with the spoilage of vacuum-packed Vienna sausages by DNA-DNA hybridization. *Food Microbiol.* 11:271–274.
- Eisel, W. G., R. H. Linton, and P. M. Muriana. 1997. A survey of microbial levels for incoming raw beef, environmental sources, and ground beef in a red meat processing plant. *Food Microbiol.* 14:273–282.
- Gardner, D. W. M., and G. Shama. 2000. Modeling UV-induced inactivation of microorganisms on surface. *J. Food Prot.* 63:63–70.
- Geornaras, I., A. E. de Jesus, E. van Zyl, and A. von Holy. 1996. Bacterial populations associated with poultry processing in a South African abattoir. *Food Microbiol.* 13:457–465.
- Gustavsson, P., and E. Borch. 1993. Contamination of beef carcasses by psychrotropic *Pseudomonas* and *enterobacteriaceae* at different stages along the processing line. *Int. J. Food Microbiol.* 20:67–83.
- Holt, P. S., B. W. Mitchell, K. H. Seo, and R. K. Gast. 1999. Use of negative air ionization for reducing airborne levels of *Salmonella enterica* serovar Enteritidis in a room containing infected caged layers. *J. Appl. Poult. Res.* 8:440–446.
- Jay, J. 2000. Modern food microbiology. Aspen Publishers, Gaithersburg, Md.
- Kang, Y. J., and J. F. Frank. 1989. Biological aerosols: a review of airborne contamination and its measurement in dairy processing plants. *J. Food Prot.* 52:512–524.
- Knudtson, L. M., and P. A. Hartman. 1993. Enterococci in pork processing. *J. Food Prot.* 56:6–9.
- Kotula, A. W., and B. S. Emswiler-Rose. 1988. Airborne microorganisms in pork processing establishment. *J. Food Prot.* 51:936–937.
- Lutgring, K. R., R. H. Linton, N. J. Zimmerman, M. Peugh, and J. Heber. 1997. Distribution and quantification of bioaerosols in poultry processing plants. *J. Food Prot.* 60:804–810.
- Mayr, D., R. Margesin, E. Klingsbichel, E. Hartungen, D. Jenewein, F. Schinner, and T. D. Märk. 2003. Rapid detection of meat spoilage by measuring volatile organic compounds by using proton transfer reaction mass spectrometry. *Appl. Environ. Microbiol.* 69:4679–4705.
- Pearce, R. A., J. J. Sheridan, and D. J. Bolton. 2006. Distribution of airborne microorganisms in commercial pork slaughter processes. *Int. J. Food Microbiol.* 107:189–191.
- Prendergast, D. M., D. J. Daly, J. J. Sheridan, D. A. McDowell, and I. S. Blair. 2004. The effect of abattoir design on aerial contamination levels and the relationship between aerial and carcass contamination levels in two Irish beef abattoirs. *Food Microbiol.* 21:589–596.
- Rahkio, T. M., and H. J. Korkeala. 1997. Airborne bacteria and carcass contamination in slaughterhouses. *J. Food Prot.* 60:38–42.
- Ren, T. J., and J. F. Frank. 1992. Measurement of airborne contamination in two commercial ice cream plants. *J. Food Prot.* 55:43–47.
- Richardson, L. J., C. L. Hofacre, B. W. Mitchell, and J. L. Wilson. 2003. Effect of electrostatic space charge on reduction of airborne transmission of *Salmonella* and other bacteria in broiler breeders in production and their progeny. *Avian Dis.* 47:1352–1361.
- Sofos, J. N., S. L. Kochavar, J. O. Reagan, and G. C. Smith. 1999. Extent of beef carcass contamination with *Escherichia coli* and probabilities of parsing regulatory criteria. *J. Food Prot.* 62:234–238.
- St. Georges, S. D., and J. J. R. Feddes. 1995. Removal of airborne swine dust by electrostatic precipitation. *Can. Agric. Eng.* 37:103–107.
- Whitfield, F. B. 1998. Microbiology of food taints. *Int. J. Food Sci. Technol.* 33:31–51.
- Whyte, P., J. D. Collins, K. McGill, C. Monahan, and H. O'Mahony. 2001. Distribution and prevalence of airborne microorganisms in three commercial poultry processing plants. *J. Food Prot.* 64:388–391.